Reward and Uncertainty Favor Risky Decision-Making in Pilots: Evidence from Cardiovascular and Oculometric Measurements

Mickaël Causse · Bruno Baracat · Josette Pastor · Frédéric Dehais

Abstract In this paper we examined plan continuation error (PCE), a well known error made by pilots consisting in continuing the flight plan despite adverse meteorological conditions. Our hypothesis is that a large range of strong negative emotional consequences, including those induced by economic pressure, are associated with the decision to revise the flight plan and favor PCE. We investigated the economic hypothesis with a simplified landing task (reproduction of a real aircraft instrument) in which uncertainty and reward were manipulated. Heart rate (HR), heart rate variability (HRV) and eye tracking measurements were performed to get objective clues both on the cognitive and emotional state of the volunteers. Results showed that volunteers made more risky decisions under the influence of the financial incentive, in particular when uncertainty was high. Psychophysiological examination showed that HR increased and total HRV decreased in response to the cognitive load generated by the task. In addition, HR also increased in response to the financially motivated condition. Eventually, fixation times increased when uncertainty was high, confirming the difficulty in obtaining/interpreting information from the instrument in this condition. These results support the assumption that risky-decision making observed in pilots can be, at least partially, explained by a shift from cold to hot (emotional) decision-making in response to economic constraints and uncertainty.

Keywords Heart rate · Heart rate variability · Eye tracking · Aviation safety · Decision making · Reward

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Introduction

51% of accidents occur during arrival whereas this phase represents only 4% of exposure, i.e. the percentage of flight time based on flight duration of 1.5 h (Boeing 2005). A study conducted by MIT (Rhoda and Pawlak 1999) has demonstrated that in 2,000 cases of approaches under thunderstorm conditions, two aircrews out of three keep on landing in spite of adverse meteorological conditions instead of going-around to perform a new attempt to land more securely or to divert to another airport. Many experiments have addressed the difficulty for pilots to revise their flight plan and several cognitive and psycho-social explanatory hypotheses have been put forward (Causse et al. in press; Causse et al. in press; Goh and Wiegmann 2002; O' Hare and Smitheram 1995). This phenomenon is called plan continuation error (PCE) and is defined as the "failure to revise a flight plan despite emerging evidence that suggests it is no longer safe" (Orasanu et al. 2001). In other words, PCE results when the pilot fails to perceive the changing context of the airspace and subsequently consider alternate flight plans (McCoy and Mickunas 2000). The failure to revise a plan is attributed to overconfidence (Goh and Wiegmann 2001), tolerance of risk (Pauley et al. 2008), lack of experience (Burian et al. 2000) or loss of situation awareness (Orasanu et al. 2001). Another form of explanation for PCE may reside in the impact of the large range of strong negative emotional consequences associated with the decision to go-around. Indeed, a go-around increases the uncertainty and the level of stress and it may lead to great difficulties to reinsert the aircraft in the traffic. Moreover, a go-around has important financial consequences for the airline due to extra fuel consumption. One now-defunct airline used to pay passengers one dollar for each minute their flight was late until a crew attempted to land through a thunderstorm and crashed (Nance 1986). According to Orasanu (2001), airlines also emphasize fuel economy and getting passengers to their destinations rather diverting the flight, perhaps inadvertently sending messages to their pilots concerning safety versus productivity. Those blurred messages create conflicting motives, which can affect unconsciously pilots' risk assessments and the course of action they choose. All these emotional pressures could alter the rational reasoning by shifting decision-making constraints from safety rules to economic ones.

Neuroeconomics studies have explored the effects of monetary reward/punishment on cognition. Taylor et al. (2004) highlighted the efficiency of financial incentive to bias working memory and object recognition and Dreher et al. (2006) showed that reward speeds up decision-making. The dorsolateral prefrontal cortex (DLPFC) is involved in higher cognition, such as reasoning, whereas the orbitofrontal cortex, which participates in emotional mechanisms, modulates the anticipation of regret linked to financial loss (Coricelli et al. 2005). Therefore, reward/punishment manipulation may interfere both with cognition and emotion and a parallel could be drawn between neuroeconomics studies and pilots placed in a conflict situation between systems of punishment (extra fuel consumption, fatigue caused by a second landing attempt etc.) and reward (bring passengers without delay). Indeed, financial reward is associated with neuronal activities in regions that respond also to emotions and primary reinforcers (Elliott et al. 2003).

Today, it is assumed that emotion and stress jeopardize decision-making relevance and cognitive functioning in particular in complex tasks (like piloting) that involve the prefrontal cortex (Dehais et al. 2003; Schoofs et al. 2008). Emotion is closely linked with rational processing in risk assessment situation when uncertainty is high (Damasio, 1994). Abelson and Clarke (1963) were the firsts to oppose reason-based cold cognition to emotionally influenced hot cognition. Many authors have since confirmed the existence of a shift from rational cold reasoning to emotional hot reasoning and its cerebral underpinning has been demonstrated (Mitchell and Phillips 2007; Drevets and Raichle 1998). For instance, Goel and Dolan (2003) have explored the neural network involved in cold reasoning versus hot reasoning. In their experiment, participants had to solve syllogisms during an fMRI experiment. Half of the syllogism verbal content was neutral (cold) whereas the other half was emotionally salient (hot). Hot reasoning resulted in enhanced activation in ventromedial prefrontal cortex (VMPFC) whereas cold reasoning resulted in enhanced activity in DLPFC, highlighting that different regions are recruited during reasoning according to the emotional state of participants. Such a cerebral shift may affect accuracy of decision making and/or reasoning (Simpson et al. 2001).

The shifting from cold to hot decision-making may be revealed by changes in the autonomic nervous system (ANS) activity (Buchanan et al. 2010; Thayer et al. 2009) and can be measured by heart rate (HR), blood pressure (Boutcher and Boutcher 2006; Causse et al. 2010; Dehais et al. 2011; Sosnowski et al. 2004) or heart rate variability (HRV) (Capa et al. 2008; Duschek et al. 2009; Ryu and Myung 2005). For instance, Brosschot and Thayer (2003) found that HR varied during positive and negative affect. It is worth noticing that increased HR and/or decreased HRV may be caused by an increased neocortical activity (Backs 1995; Boucsein and Backs 2000).

Flying an aircraft strongly involves visual attention processes. Since the automation of flight desk, the pilot's activity mainly aims at monitoring the embedded systems and not to control manually the flight itself. It is particularly true during the landing, a highly automated flight phase, where pilots have to focus on several visual parameters (e.g. altitude, heading) to perform a Go/No-Go decision-making. Indeed when pilots decide to go-around, the first major action is to push the throttle to trigger the automated go-around maneuver. In a second time, the go-around initiates a missed approach procedure, an optional flight segment that is depicted in the flight plan (altitude to reach, heading etc.).

Our hypothesis is that PCE may be, at least in part, due to a shift from cold reasoning to hot reasoning. This shift may be the result of the large range of strong negative emotional consequences linked with the decision to go-around. In this perspective, hot reasoning is less rational from a safety point of view and integrates criteria that are oriented toward company's financial interest. In this study, we proposed to investigate this hypothesis with a simplified landing task inspired by neuroeconomics protocols in which uncertainty and financial reward were manipulated. Cardiovascular measurements were performed to get objective clues both of the cognitive and emotional states of the volunteers. Eye tracking technique were also used as it provides interesting insights as the analysis of eye fixations is a reliable indicator of task complexity or attentional demand (Backs and Walrath 1992) and is related to the difficulty in obtaining/interpreting information from an instrument (Wilson and Eggemeier 1991) whereas the absence of eye gaze on relevant information may suggest environmental misperception (Sarter et al. 2007). In addition, eye tracking may constitute a good clue to understand some particular PCE (e.g. Controlled Flight Into Terrain accidents) where pilots keep on landing despite visual ground proximity alarms. Indeed physiological stress is known to provoke visual tunneling or cognitive lock up (Bahrick et al. 1952; Easterbrook 1991; Weltman and Egstrom 1966), phenomenon that led pilots to neglect critical information.

Methods

Participants

19 young physically and psychiatrically healthy volunteers were recruited from the local population to participate in the experiment (mean age = 20.9, SD = 1.59). All participants were students in aeronautics and were pilots (68.42%) or were preparing their flight license (31.58%). They were all right-handed as measured by the Edinburgh handedness inventory (Oldfield 1971). Volunteers gave their informed consent before participation. Volunteers were paid for participating and were told that they would earn extra money according to their actions during the task. Subjects were also told that they would earn only a percentage of the amount of money presented on the screen after each response. For ethical reasons, they all won the maximum amount of money.

Experimental Paradigm

We used a 2 $\times$ 2 factorial design crossing two independent variables, the type of incentive and the uncertainty. The task was based on 480 $\times$ 480 pixels simplified reproduction of a real flight instrument, the ILS (Instrument Landing System). An ILS consists of two independent sub-systems, one providing lateral guidance (localizer), the other vertical guidance (glide slope or glide path) to aircraft approaching a runway. This instrument is displayed in the cockpit within the primary flight display. We used a simplified version of the primary flight display of an Airbus A320 with only the ILS (we removed other instrument like airspeed of altitude). This instrument supports the pilot's decision-making during landing without external visibility.

The volunteers were instructed that they were flying a plane that had reached the decision altitude (the point of the approach where the pilot must decide if the flight has to be aborted or not) and that they were allowed to avoid landing if they believed that landing was unsafe. Decisions were based on the two elements of the ILS: the localizer and the glide slope, which provide lateral and vertical guidance to adjust the trajectory of the aircraft to land on the runway. The information was given by two rhombuses, like in real aircraft, displayed below and on the right of the artificial horizon (Fig. 1). It was reminded to volunteers that the landing was safe when both rhombuses were close to the center of their axis and that the farthest from the center the rhombuses were, the higher was the risk of crash. They were instructed that rhombuses positions represented vertical/lateral current position of the aircraft regarding an ideal approach flight path. During unstabilized approach, events may be strongly unpredictable and results of actions cannot be well anticipated. In our study, we reproduced this uncertainty thanks to the level of ambiguity of information provided by the instrument. Indeed, stimuli that supported the landing decision were manipulated according to two levels of uncertainty: low and high (Fig. 2). This ambiguity emerged when the rhombuses were in "fuzzy" positions (i.e. in between a straight go-around and a safe landing). Such ambiguity generated uncertainty as the feedback (accuracy and or financial outcome) linked with the decision was unpredictable. In the landing condition with low uncertainty, the decision making was straightforward:

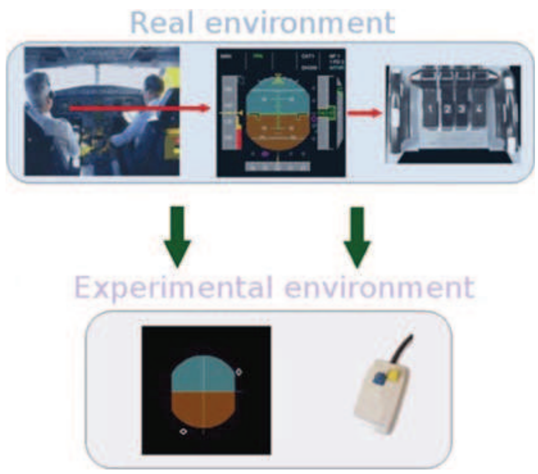


Fig. 1 Simplified reproduction of the decision-making environment during the landing phase. In the *upper part*, the real environment. From *left to right*: the real cockpit, a zoom on the main instrument with ILS and the throttle. In the *bottom part*, the experimental environment. From *left to right*: the simplified main instrument with only the two rhombuses of the ILS (in *white*) and the response pad that replaced the throttle

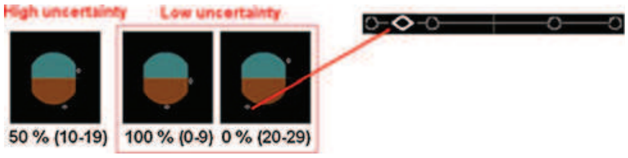


Fig. 2 Categorization of the level of uncertainty according to a score, between 0 and 29, calculated from the rhombus positions. The position were counterbalanced to avoid laterality effects. The order of presentation of the stimuli was randomized

either the rhombuses were very far from their respective center, requiring a go-around (likelihood of successful landing: 0%), or they were very close, requiring a landing acceptance (likelihood of successful landing: 100%). In the landing conditions with high uncertainty, rhombuses had borderline positions (not very far, not very close from the center) and the likelihood (unknown by the subjects) of a successful landing or a crash was 50%. Within a run, there was no repetition of a same rhombus pattern. These changes in the level of uncertainty allowed the reduction of habituation to stimuli and promoted a sustained high level of reasoning throughout the experiment.

Two types of runs were presented during the experiment, neutral and financial. For each trial, the volunteers indicated their choice (landing/no landing) by pressing a button on the response pad. After each response, the participants received feedback that informed on the response accuracy (OK, for a successful landing or a justified go-around; NO, for an erroneous decision to land or an unjustified go-around). During the financial incentive condition, negative emotional consequences associated with a go-around were reproduced by a payoff matrix (Fig. 3). This matrix was set up to bias responses in favor of landing acceptance. A go-around was systematically punished by a financial penalty. The penalty was less important (−2€) when the go-around was justified (in the case where rhombuses were very far from their center) than when it was unjustified (−5€). This systematic punishment of the decision to go-around reproduced the systematic negative consequences associated with this latter in real-life. A successful landing was rewarded (+5€) whereas an erroneous decision to land was punished (−2€). The fact that the erroneous decision to go-around was more punished than the erroneous decision to land may appear counterintuitive but the matrix was set up in this way for two reasons. Firstly, in real-life, pilots know that crash and overrun are rather unlikely events, whereas the negative consequences associated with a go-around are systematic. The analysis of unstabilized approach confirms that accidents are rather rare in spite of frequent risk-taking (Rhoda and Pawlak 1999). Secondly, introducing very rare events could have jeopardized physiological and oculometric measurements. For these reason, we were compelled to modulate the weight of the punishment rather than its frequency. At the end of each run, a global feedback indicated the percentage of correct responses, the "safety score". Moreover, at the end of the financial run, another feedback indicated the cumulative amount of money won or loss, the "financial score". These two scores were in conflict since the optimization of the "financial score" could only be done at the expense of the safety score as it necessarily implies a dangerous increase of the landing acceptance rate. Eventually, volunteers were explained that, as in real life, taking into account the flight safety was essential in this experiment.

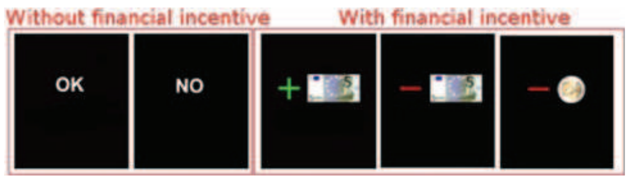


Fig. 3 The feedbacks displayed after each decision making. Without incentive, only the accuracy feedback was delivered (OK/NO), with financial incentive, the monetary consequences were also displayed after the accuracy feedback

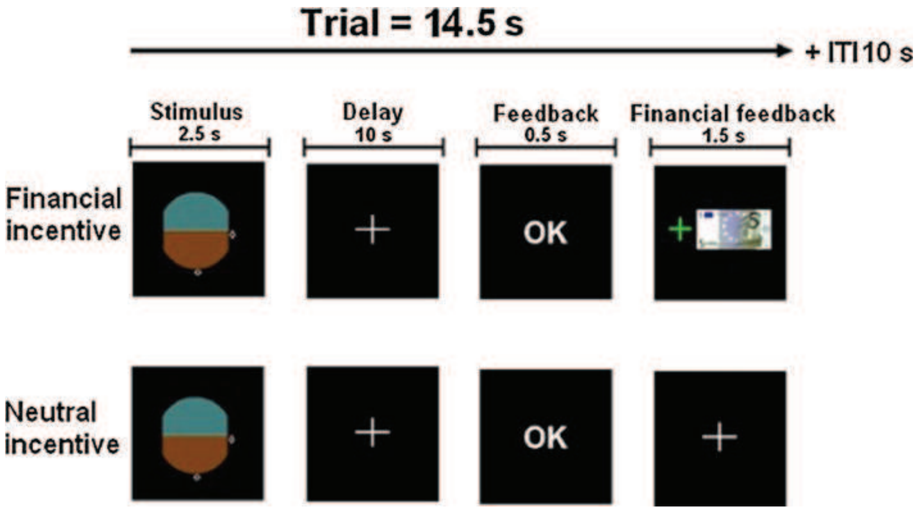
Stimuli Presentation

Stimulus display and data acquisition were done with Cogent 2000 v125 running under Matlab environment (Matlab 7.2.0.232, R2006a, The MathWorks, USA). Each trial (see Fig. 4) consisted in a presentation of the stimulus (3.5 s) during which the volunteer performed the decision-making thanks to a response pad, followed after a delay (10 s) by the feedback informing of the accuracy of the response (0.5 s). During the incentive condition, the financial outcome was also displayed ({+5€}, {−5€} or {−2€}). Finally, an inter trial interval (10 s) was introduced. Before the experiment, volunteers performed two runs (neutral and financial) to become familiar with the task and the payoff matrix.

Cardiovascular Measurements

Volunteers were comfortably installed and tested in a moderately lit room, in which the illumination was held constant (background luminance: about 450 lux). The ProComp Infiniti (©Thought Technology Ltd.) was used to continuously record the cardiovascular activity. It was measured using the EKG-Flex/Pro sensor (2,048 Hz). Three electrodes connected to an extender cable were applied on the volunteer's chest. A Uni-Gel electrode was used to enhance the quality of the signal. This latter was measured in microvolts (μV) and beat to beat intervals were converted to beats per minute (bpm). Frequency domain measures of HRV were quantified through fast Fourier transform and

Fig. 4 Illustration of the stimuli presentation during the two types of experimental runs: financial and neutral



included the two main frequency bands, low-frequency power (LF, 0.03–0.15 Hz), high-frequency power (HF, 0.15–0.40 Hz) plus the very low frequency power (VLF, 0.03 Hz) and total HRV (Task Force 1996). Whereas HF frequency is known to be triggered by vagal influences, LF frequency seems dependent on a mixture of orthosympathetic and parasympathetic activity (Backs 1998). We reported absolute values for each component (natural logarithm of HRV amplitude, ms^2). Because no groups were created in our study, normalized units were not computed.

Oculometric Measurements

A Pertech head-mounted eye-tracker (type "pair of glasses") was used to analyze the volunteers' ocular behavior. It is equipped with a monocular sensor (left eye, 50 Hz) and a scene camera. Determination of gaze direction is based on pupil orientation detection: a calibration step allows correlating images of both cameras to determine precisely the eye fixations points. The device has 0.25° of accuracy and it weights 80 g which makes it likely non-intrusive for the subjects during the experimentation. A dedicated software (EyeTechLab©) provides data such as timestamps and the (x,y) coordinates of the volunteers' eye gaze on the visual scene. Fixation times on the rhombuses of the ILS were considered thanks to area of interest analysis.

Results

Statistical Analysis

Behavioral Data

All behavioral data were analyzed with Statistica 7.1 (© StatSoft). Mean reaction times (RTs) and response bias were calculated for each experimental condition. The use of response bias as variable was inspired from Taylor et al. (2004) study which also intended to measure behavioral shift in response to a biased payoff matrix. In our study, a negative response bias would correspond to a conservative behavior (lower percentage of landing acceptance than objectively expected) whereas a positive response bias would correspond to a risky behavior (higher percentage of landing acceptance than objectively expected). For instance, 65% of landing acceptance during the 50% stimuli gives a +15% response bias (65–50) concerning high uncertainty condition whereas 15% of landing acceptance during 0% stimuli and 100% of landing acceptance during 100% stimuli give a +7.5% response bias concerning low uncertainty condition (((0 + 15) + (100–100))/2). This response bias was calculated for each of the four experimental conditions. The effects of uncertainty, of the type of incentive and their interactions on RT and the response bias were examined using to two-way 2 * 2 (type of incentive * level of uncertainty) repeated measures ANOVA. Tukey's honestly significant difference post-hoc test was used to examine paired comparisons.

Cardiovascular and Oculometric Data

Mean heart rate was computed during the whole duration of three periods of interest: the baseline and the two types of runs, neutral and financial. A one-way repeated measure (baseline/neutral/financial) ANOVA was performed to assess the significance of HR changes across these three periods and Tukey's honestly significant difference post hoc test was used to examine paired comparisons. The same type of data analysis was performed on HRV values. We then examined the effect of the type of incentive, the level of uncertainty and their interactions on the heart rate during shorter time windows. Mean values were computed in the time window between the stimulus onset and 10 s post-stimulus onset. This time window was set up according to the cardiac response latency (Vila et al. 2007). Mean values of these stimulus locked data were submitted to two-way 2 $\times$ 2 (type of incentive * level of uncertainty) repeated-measures ANOVA to examine the effect of the level of uncertainty, the type of incentive and their interactions on the HR. Oculometric data were considered during the stimuli duration (2.5 s) and a two-way (incentive * uncertainty) repeated measures ANOVA was also performed. Stimulus-locked analyses were not performed on HRV because this requires a longer period of recording. For instance, Berntson et al. (2007) indicate that a minimum of 10 cycles is required to perform fast Fourier transform, in consequence only type of incentive effect was considered for HRV.

Behavioral Results

Tables 1 and 2 summarize behavioral data and main ANOVA results. Repeated measures ANOVA revealed a main effect of uncertainty on RTs ($p < .001$, $F(1,18) = 56.65$, $\eta^2 p = .76$). High uncertainty generated longer mean RTs than low uncertainty stimuli. In addition, the ANOVA revealed a main effect of the type of incentive on the RTs ($p = .001$, $F(1,18) = 16.79$, $\eta^2 p = .52$). During the financial condition, RTs were shorter than during the neutral condition, see Fig. 5. The analysis of the interactions between the level of uncertainty and the type of incentive did not show significant results ($p = .096$, $F(1,15) = 3.101$, $\eta^2 p = .15$).

The mean total outcome was high (+39.31€, SD = 11.42). It confirmed that the reward oriented decision making toward economic optimization, as a decision that would have been only oriented toward safety (systematic go-around in case of uncertainty) would have led volunteers to a negative outcome (−70€). The ANOVA showed that there was a main effect of the uncertainty ($p < .001$, $F(1,18) = 21.81$, $\eta^2 p = .54$) and a main effect of the incentive ($p < .001$, $F(1,18) = 94.49$, $\eta^2 p = .83$) on the magnitude of the response bias. In addition, the ANOVA also revealed an interaction effect between these two variables ($p = .013$, $F(1,18) = 7.50$, $\eta^2 p = .29$): the financial incentive provoked an increase of the likelihood to accept a landing and this increase was higher when the uncertainty was elevated. Concerning the financial incentive condition, the response bias shifts from +2.89% when the uncertainty was low, to +32.36% when the uncertainty was high ($p < .001$), see Fig. 6.

Cardiovascular Results

Tables 3 and 4 summarize cardiovascular data and main ANOVA results. The analysis revealed that the HR was significantly different across the three periods ($p < .001$, $F(2.36) = 14.88$ $\eta^2 p = .49$), see Fig. 7. The HSD post-hoc test demonstrated that the mean HR was higher during the two runs than during the baseline ($p < .001$ in both

Table 1 Average value and standard deviation using behavioral variables according to the level of uncertainty and the type of incentive (N = 19)

	Neutral		Financial	
	Low uncertainty	High uncertainty	Low uncertainty	High uncertainty
TR (ms)	1,334.83 ± 177.70	1,561.16 ± 177.97	1,270.89 ± 174.77	1,407.39 ± 163.43
Bias (%)	−4.73 ± 5.39	12.36 ± 18.66	2.89 ± 5.08	32.36 ± 12.62

Table 2 Main ANOVA results and interactions (* $p \leq .05$; *** $p \leq .001$) using behavioral variables according to the level of uncertainty and the type of incentive (N = 19)

Effect	*df*	*F*	MSE	*p*	η^2_p
RT					
Uncertainty	1.18	56.65	10,524	<.001***	.76
Incentive	1.18	18.79	11,861	<.001***	.52
Uncertainty × Incentive	1.18	3.101	11,413	<.096	.15
Response bias					
Uncertainty	1.18	21.81	166.23	<.001***	.54
Incentive	1.18	94.49	109.06	<.001***	.83
Uncertainty × Incentive	1.18	7.50	96.78	.013*	.29

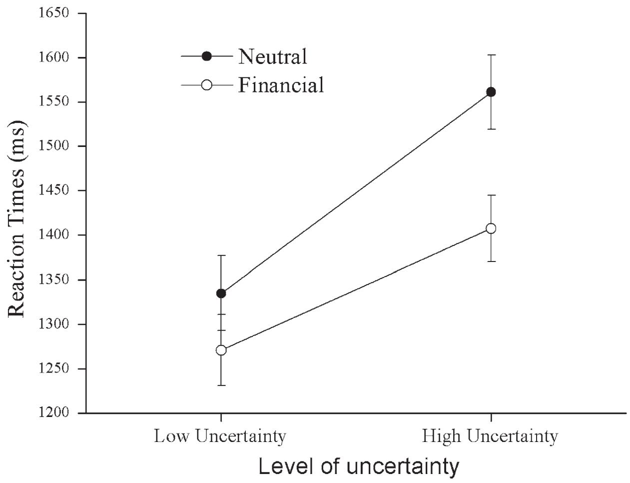


Fig. 5 Reaction time (ms) according to the level of uncertainty and the type of incentive. *Bars* represent the standard error (N = 19)

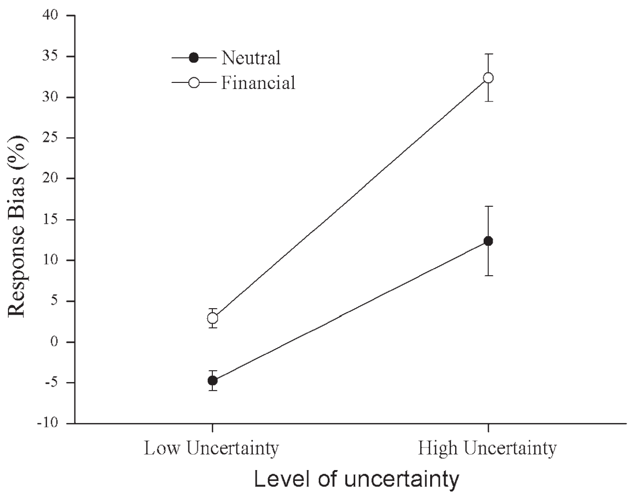


Fig. 6 Response bias (%) according to the level of uncertainty and the type of incentive. A positive response bias demonstrated a landing acceptance beyond the objective expectancies (for instance, 55% of landing acceptance during the high uncertainty condition with financial incentive gives a 5% response bias). *Bars* represent the *standard error* (N = 19)

comparisons). In addition, HSD post-hoc test showed an effect of the type of incentive: the mean HR was higher during the run with financial incentive than the neutral one ($p = .018$). Newman-Keuls method confirmed this outcome and classified the baseline, the neutral run and the financial run as three independent homogeneous groups. The mean HR was 70.15 bpm (SD = 7.63) during the baseline, 71.94 bpm (SD = 5.88) during the neutral run and 74.04 bpm (SD = 6.39) during the financial run. A separate 2 × 2 ANOVA performed on stimuli locked data showed no effect of the uncertainty but confirmed that HR was higher when the decision-making was performed under the financial pressure than during the neutral condition ($p < .023$, $F(1.18) = 5.57$ $\eta^2p = .29$).

We then examined the HRV variations (VLF, LF, HF and total HRV) across the three periods of interest. The one-way repeated-measures ANOVA revealed a main effect of the period of interest on VLF ($p = .046$, $F(2,36) = 3.30$, $\eta^2p = .18$), LF ($p = .023$, $F(2,36) = 4.24$, $\eta^2p = .22$), HF ($p = .050$, $F(2,36) = 2.91$, $\eta^2p = .16$) and on the total HRV ($p < .001$, $F(2,60) = 5.47$, $\eta^2p = .26$), see Fig. 8. Paired comparisons showed that VLF, LF, HF and total HRV were lower during neutral run and financial run than during rest state (respectively $p = .034$ & $p = .032$; $p = .017$ and $p = .016$; $p = .042$ and $p = .048$; $p = .007$ and $p = .007$). Contrary to HR, there was no effect of the type of incentive on HRV variables.

Eye Tracking Results

Tables 5 and 6 summarize eye tracking data and main 2 × 2 ANOVA results. There was a significant effect of uncertainty on the fixation time ($p < .001$, $F(1,18) = 1{,}109$, $\eta^2p = .98$), see Fig. 9. The stimuli with a high level of ambiguity generated a strong increase of the time spent analyzing the rhombuses positions in comparison to the stimuli with low ambiguity. There was no main effect of the type of incentive.

Discussion

Our experiment was designed to understand pilots' trend to land despite bad landing conditions. We investigated the impact of an economic pressure, namely the cost of a go-around, on risk taking during a plausible landing-decision situation. In this experiment, both uncertainty and type of incentive were manipulated. Our assumption was that pilots frame their decision to keep on landing in terms of potential losses, such as money spent of fuel consumption (O' Hare and Smitheram 1995). Indeed, an airline that emphasizes productivity (e.g. on time arrivals or saving fuel) may unconsciously set up conflicts with safety. Pilots may be willing to take a risk with safety (a possible loss) to arrive on time (a sure benefit). Our behavioral, physiological and oculometric results tend to confirm that the risky decision to land in pilots may be explained by decision-making criteria shifting. Cold reasoning appeared to be more analytic and objective whereas hot reasoning was associated with a search for reward at the expense of safety.

On one hand, longer RTs and greater fixation times suggest that in the high uncertainty condition, the task was very demanding and required further analysis of the stimuli. Longer fixations times are generally believed to be an

Table 3 Average value and standard deviation using cardiovascular variables according to the level of uncertainty and the type of incentive (N = 19)

	Rest	Neutral		Financial	
		Low uncertainty	High uncertainty	Low uncertainty	High uncertainty
HR (bpm)	70.15 ± 7.63	72.06 ± 5.42	72.32 ± 6.05	73.989 ± 6.89	74.09 ± 6.29
VLF (ms^2)	268.70 ± 407.50	144.69 ± 151.15		146.21 ± 156.44	
LF (ms^2)	545.43 ± 536.38	315.22 ± 311.28		314.45 ± 299.30	
HF (ms^2)	471.79 ± 439.50	262.29 ± 311.45		268.495 ± 378.95	
Total HRV (ms^2)	1,285.93 ± 1,243.98	723.73 ± 692.86		727.64 ± 760.91	

Table 4 Main ANOVA results, interactions and Tukey's HSD post hoc (* $p \leq .05$; *** $p \leq .001$) using cardiovascular variables according to the period, the level of uncertainty and the type of incentive (N = 19)

Effect	*df*	*F*	MSE	*p*	η^2_p	Tukey's HSD
HR						
Period	2.36	14.88	4	<.001***	.49	Neutral & Financial > Baseline; Financial > Neutral
Uncertainty	1.18	0.95	1.1	.343	.06	
Incentive	1.18	6.32	5.70	.023*	.29	
Uncertainty × Incentive	1.18	0	0.9	.95	.00	
VLF						
Period	2.36	3.30	24.504	.046*	.18	Neutral & Financial > Baseline
LF						
Period	2.36	4.24	66.732	.023*	.22	Neutral & Financial > Baseline
HF						
Period	2.36	2.91	77.961	.050*	.16	Neutral & Financial > Baseline
Total HRV						
Period	2.36	5.47	305.646	<.001***	.26	Neutral & Financial > Baseline

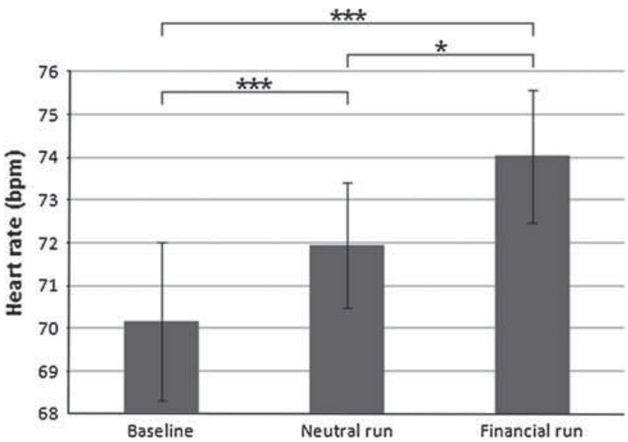


Fig. 7 Mean heart rate (bpm) across the three periods of interest: at rest (*baseline*), and during the neutral run and the financial run. The HR was significantly lower during the baseline than the two runs and was more elevated during the financial run than the neutral one (* $p \leq .05$; *** $p \leq .001$). These results showed an effect of the mental load generated by the task (for both types of runs) and an effect of the type of incentive. *Bars* represent the standard error (N = 19)

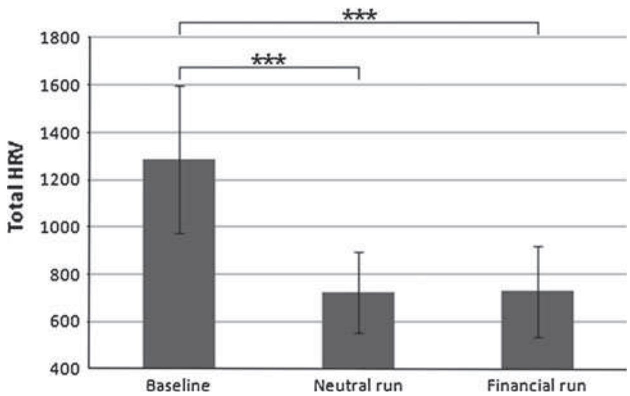


Fig. 8 Mean total HRV (ms^2) across the three periods of interest: at rest (*baseline*), the neutral run and the financial run. The total HRV was significantly lower during the two runs than during the baseline, showing an effect of the mental load generated by the task (for both types of runs) (*** $p \leq .001$). *Bars* represent the standard error ($N = 19$)

indication of a participant's difficulty extracting information from a display (Goldberg and Kotval 1999; Wilson and Eggemeier 1991; Fitts et al. 1950). On the other hand, it is interesting to note that when high uncertainty condition was

Table 5 Average value and standard deviation using oculometric variable according to the level of uncertainty and the type of incentive (N = 19)

	Neutral		Financial	
	Low uncertainty	High uncertainty	Low uncertainty	High uncertainty
Fixation times (s)	0.87 ± 0.14	1.92 ± 0.23	0.82 ± 0.17	1.76 ± 0.35

Table 6 Main ANOVA results and interactions (*** $p \leq .001$) using oculometric variable according to the level of uncertainty and the type of incentive (N = 19)

Effect	*df*	*F*	MSE	*p*	η^2_p
Fixations times					
Uncertainty	1.18	1.58	0.07	<.001***	.98
Incentive	1.18	1,338.70	0.01	.662	.01
Uncertainty × Incentive	1.18	1.83	0.01	.194	.10

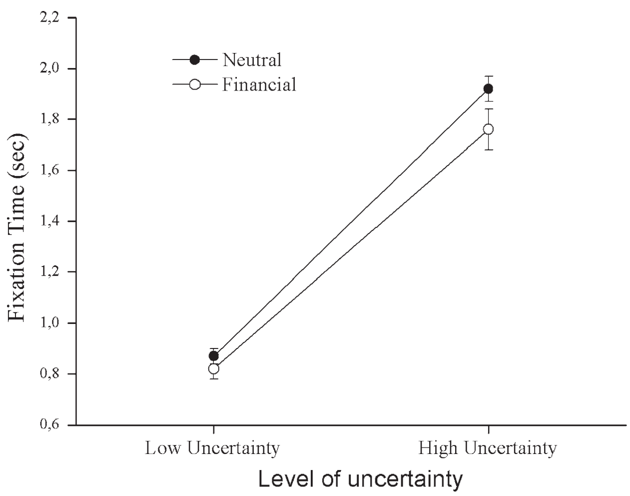


Fig. 9 Fixation time (sec) according to the level of uncertainty and the type of incentive. *Bars* represent the standard error (N = 19)

combined with the financial pressure, the volunteers showed a shift toward hot reasoning. Firstly, compared to the neutral condition, RTs were dramatically reduced, which suggest a lower depth of reasoning before reaching decision-making in presence of the financial incentive. Secondly, the volunteers clearly changed their response criteria in favor of economic optimization as they made more risky decisions to avoid the risk of a penalty in the case of a go-around. As a matter of fact, this behavior led the volunteers to more crashes. Interestingly, this shift could be conscious as this risky decision-making occurred in spite of a proper analysis of the situation, at least from a quantitative point of view, as the time spent on the rhombuses at the time of the decision-making was equivalent with or without the financial incentive. This gaze pattern shows that PCE can result from a less rational reasoning in response to conflicting motives created by the financial pressure and helps to understand some particular PCE that led to Controlled Flight Into Terrain accidents (CFIT), where pilots kept on landing despite visual ground proximity alarms (Dehais et al. 2003). Decision making under uncertainty and time pressure is widely studied in aviation safety. In real flight operation, the crew has to face several hazards as failures are likely to occur and weather conditions (wind, visibility, icing conditions) may quickly evolved in an unpredicted way. Most of the time, go-around is taken under a high uncertainty as this situation is quite rare and the pilot lack of experience and preprogrammed knowledge. We simulated uncertainty thanks to the level of ambiguity of information provided by the ILS instrument. We assume that our landing task was a very simplified situation compared to real flight conditions that are much more complex in terms of information processing. Nevertheless the analysis of the physiological responses showed that the task has generated notable energy mobilization and psychological stress as the mean HR was significantly higher during task in comparison to the resting state (Boutcher and Boutcher 2006; Causse et al. 2010; Sosnowski et al. 2004). In the same way, the fall of the total HRV during both runs in comparison to rest state is coherent with an increased mental workload (Ryu and Myung 2005; Thayer et al. 2009).

Again, though the economical consequences of this task had nothing to compare with real flight issues, the payoff matrix designed to reproduce the negative consequences linked with the decision to go-around was efficient enough to provoke risky behavior such as PCE. Indeed, it has incited volunteers to maximize their monetary reward and biased their response criterion from safety to economic considerations in spite of the fact that all participants were told that as in real life, taking into account the flight safety was essential in this experiment. Whole run analyses showed that the mean HR was higher in the financially motivated condition than in the neutral condition. Although the magnitude of the change between the two runs was moderate (2.10 bpm), it was nevertheless very significant and persistent on all participants. It should be noticed that the magnitude of this increase is consistent with the literature related to emotion induction in laboratory (Baumgartner et al. 2006; Brosschot and Thayer 2003). For instance, Brosschot (2003) showed that negative and positive emotion induction = elicited respectively an HR rise of 2.14 and 1.06 bpm. This increased HR, well known to occur in real-life gamblers (Meyer et al. 2000), demonstrated that the financial incentive has provoked an emotional arousal. We initially hypothesized that financial incentive will induced a shift from cold to hot reasoning in our volunteers, where hot reasoning refers to emotional processing and cold reasoning relied on cognitive processing (Goel and Dolan 2003; Schaefer et al. 2003). As these studies have indicated that emotional processing activates VMPFC and that increased heart rate in an indication of VMPFC recruitment (Ziegler et al. 2009) we assume that this shift effectively occurred. A final interesting point was that HR appeared to be more sensitive to a moderate emotional arousal as HRV was not impacted by the type of incentive (neutral or financial). It also suggests that the autonomic activity can be differentially affected by central stimulation and in a much more complex way than a monolithic activation reflecting and increased arousal. In this sense, a study of McCraty et al. (1995) showed that HR and HRV variations can be independent during the experience of anger and appreciation. These outcomes confirm the importance of using several sensors to monitor emotional or cognitive state of operators like pilots (Veltman 2002; Yao et al. 2008; Dahlstrom and Nahlinder 2006). As long as the operator is a key agent in charge of complex systems, the choice of relevant measurements able to predict his performance in order to provide real-time assistance is a great challenge. For instance, HR measurement could be a reliable indication of the experience of a deleterious emotion and gives the opportunity to react quickly with countermeasures (e.g. a simple informative message with actions to perform) before reaching an irreversible situation. In the same way, gaze-tracking could be used to detect that some critical information (e.g. alarm) are difficult to interpret or neglected. We reproduced the same experiment in fMRI with 15 volunteers in order to examine the brain regions involved in the shift from cold to hot reasoning. Preliminary results are consistent with this study: we observed an increase of risky decision in presence of the monetary incentive when uncertainty is high. Moreover, the financial incentive and the uncertainty enhanced the activity of “emotional” neural pathways and modulated visual areas recruitment (Causse et al. 2009).

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References

Abelson, R., & Clarke, D. D. (1963). Computer simulation of “hot” cognition. In S. S. Tomkins & S. Messick (Eds.), *Computer simulation of personality*. New York: John Wiley & Sons.

Backs, R. (1995). Going beyond heart rate: autonomic space and cardiovascular assessment of mental workload. *The International Journal of Aviation Psychology, 5*(1), 25–48.

Backs, R. (1998). A comparison of factor analytic methods of obtaining cardiovascular autonomic components for the assessment of mental workload. *Ergonomics, 41*(5), 733–745.

Backs, R., & Walrath, L. (1992). Eye movement and pupillary response indices of mental workload during visual search of symbolic displays. *Applied Ergonomics, 23*(4), 243–254.

Bahrick, H., Fitts, P., & Rankin, R. (1952). Effect of incentives upon reactions to peripheral stimuli. *Journal of Experimental Psychology, 44*(6), 400–406.

Baumgartner, T., Esslen, M., & Jäncke, L. (2006). From emotion perception to emotion experience: Emotions evoked by pictures and classical music. *International Journal of Psychophysiology, 60*(1), 34–43.

Berntson, G., Quigley, K., & Lozano, D. (2007). Cardiovascular psychophysiology. In L. G. Tassinary & G. G. Berntson (Eds.), Handbook of psychophysiology (3rd ed) (pp. 182–210). Cambridge, UK: Cambridge University Press.

Boeing. (2005). Summary of Commercial Jet Airplane Accidents Worldwide Operations 1959–2004.

Boucsein, W., & Backs, R. W. (2000). Engineering psychophysiology as a discipline: Historical and theoretical aspects. In R. W. Backs & W. Boucsein (Eds.), *Engineering psychophysiology: Issues and applications* (pp. 3–29). Mahwah, NJ: Erlbaum.

Boutcher, Y. N., & Boutcher, S. H. (2006). Cardiovascular response to Stroop: Effect of verbal response and task difficulty. *Biological Psychology, 73*(3), 235–241.

Brosschot, J. F., & Thayer, J. F. (2003). Heart rate response is longer after negative emotions than after positive emotions. *International Journal of Psychophysiology, 50*(3), 181–187.

Buchanan, T., Driscoll, D., Mowrer, S., Sollers, J., I. I. I., Thayer, J., Kirschbaum, C., et al. (2010). Medial prefrontal cortex damage affects physiological and psychological stress responses differently in men and women. *Psychoneuroendocrinology, 35*(1), 56–66.

Burian, B., Orasanu, J., & Hitt, J. (2000). Weather-related decision errors: Differences across flight types. In *Proceedings of the HFES 2000*, Santa Monica, CA, USA.

Capa, R., Audiffren, M., & Ragot, S. (2008). The interactive effect of achievement motivation and task difficulty on mental effort. *The International Journal of Psychophysiology, 70*(2), 144–150.

Causse, M., Dehais, F., Péran, P., Demonet, J.-F., Sabatini, U., & Pastor, J. (2009). Monetary incentive provokes hazardous landing decision making by enhancing the activity of “emotional” neural pathways. *NeuroImage, 47*(Supplement 1), 117.

Causse, M., Dehais, F., Arexis, M., & Pastor, J. Cognitive aging and flight performances in general aviation pilots. *Aging, Neuropsychology and Cognition* (in press).

Causse, M., Dehais, F., & Pastor, J. Executive functions and pilot characteristics predict flight simulator performance in general aviation pilots. *The International Journal of Aviation Psychology* (in press).

Causse, M., Sénard, J., Démonet, J., & Pastor, J. (2010). Monitoring cognitive and emotional processes through pupil and cardiac response during dynamic versus logical task. *Applied psychophysiology and biofeedback, 35*(2), 115–123.

Coricelli, G., Critchley, H. D., Joffily, M., O'Doherty, J. P., Sirigu, A., & Dolan, R. J. (2005). Regret and its avoidance: a neuroimaging study of choice behavior. *Nature Neuroscience, 8*(9), 1255–1262.

Dahlstrom, N., & Nahlinder, S. (2006). A comparison of two recorders for obtaining in-flight heart rate data. *Applied psychophysiology and biofeedback, 31*(3), 273–279.

Damasio, A. (1994). *Descartes' error: Emotion, reason, and the human brain.* New York: Grosset/Putnam.

Dehais, F., Sisbot, E-A., Alami, R., Causse, M. (2011). Physiological and Subjective Evaluation of a Human-Robot Object Hand Over Task. *Applied Ergonomics.* doi:10.1016.

Dehais, F., Tessier, C., & Chaudron, L. (2003). *GHOST: Experimenting conflicts coutermeasures in the pilot's activity*. Paper presented at the IJCAI, Acapulco, Mexique.

Dreher, J. C., Kohn, P., & Berman, K. F. (2006). *Neural coding of distinct statistical properties of reward information in humans. Cerebral Cortex, 16*(4), 561.

Drevets, W., & Raichle, M. (1998). Reciprocal suppression of regional blood flow during emotional versus higher cognitive processes: Implications for interactions between emotion and cognition. *Cognition and Emotion, 12*(3), 353–385.

Duschek, S., Muckenthaler, M., Werner, N., & Reyes del Paso, G. (2009). Relationships between features of autonomic cardiovascular control and cognitive performance. *Biological Psychology, 81*(2), 110–117.

Easterbrook, S. (1991). Handling conflict between domain descriptions with computer-supported negotiation. *Knowledge acquisition, 3*(3), 255–289.

Elliott, R., Newman, J., Longe, O., & Deakin, J. (2003). Differential response patterns in the striatum and orbitofrontal cortex to financial reward in humans: a parametric functional magnetic resonance imaging study. *Journal of Neuroscience, 23*(1), 303.

Fitts, P., Jones, R., & Milton, J. (1950). Eye Movements of Aircraft Pilots During Instrument-Landing Approaches. *Aeronautical Engineering Review, 9*(2), 24–29.

Goel, V., & Dolan, R. (2003). Reciprocal neural response within lateral and ventral medial prefrontal cortex during hot and cold reasoning. *Neuroimage, 20*(4), 2314–2321.

Goh, J., & Wiegmann, D. (2001). Visual flight rules flight into instrument meteorological conditions: An empirical investigation of the possible causes. *The International Journal of Aviation Psychology, 11*(4), 359–379.

Goh, J., & Wiegmann, D. (2002). Human factors analysis of accidents involving visual flight rules flight into adverse weather. *Aviation Space and Environmental Medicine, 73*(8), 817.

Goldberg, J., & Kotval, X. (1999). Computer interface evaluation using eye movements: Methods and constructs. *International Journal of Industrial Ergonomics, 24*(6), 631–645.

McCoy, C. E., & Mickunas, A. (2000). *The role of context and progressive commitment in plan continuation error. Proceedings of the IEA 2000 and HFES 2000 Congress*. CA: Santa Monica.

McCraty, R., Atkinson, M., Tiller, W., Rein, G., & Watkins, A. (1995). The effects of emotions on short-term power spectrum analysis of heart rate variability. *The American journal of cardiology, 76*(14), 1089–1093.

Meyer, G., Hauffa, B., Schedlowski, M., Pawlak, C., Stadler, M., & Exton, M. (2000). Casino gambling increases heart rate and salivary cortisol in regular gamblers. *Biological Psychiatry, 48*(9), 948–953.

Mitchell, R., & Phillips, L. (2007). The psychological, neurochemical and functional neuroanatomical mediators of the effects of positive and negative mood on executive functions. *Neuropsychologia, 45*(4), 617–629.

Nance, J. (1986). *Blind trust: How deregulation has jeopardized airline safety and what you can do about it*. New York: William Morrow and co.

O' Hare, D., & Smitheram, T. (1995). "Pressing on" into deteriorating conditions: An application of behavioral decision theory to pilot decision making. *The International Journal of Aviation Psychology, 5*(4), 351–370.

Oldfield, R. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia, 9*(1), 97–113.

Orasanu, J., Ames, N., Martin, L., & Davison, J. (2001). Factors in aviation accidents: Decision errors. In E. Salas & G. A. Klein (Eds.), *Linking expertise and naturalistic decision making* (pp. 209–225). Mahwah, NJ: Lawrence Erlbaum Associates.

Pauley, K., O'Hare, D., & Wiggins, M. (2008). Risk tolerance and pilot involvement in hazardous events and flight into adverse weather. *Journal of Safety Research, 39*(4), 403–411.

Rhoda, D., & Pawlak, M. (1999). An assessment of thunderstorm penetrations and deviations by commercial aircraft in the terminal area. *Massachusetts Institute of Technology, Lincoln Laboratory, Project Report NASA/A-2, 3*.

Ryu, K., & Myung, R. (2005). Evaluation of mental workload with a combined measure based on physiological indices during a dual task of tracking and mental arithmetic. *International Journal of Industrial Ergonomics, 35*(11), 991–1009.

Sarter, N., Mumaw, R., & Wickens, C. (2007). Pilots' Monitoring Strategies and Performance on Automated Flight Decks: An Empirical Study Combining Behavioral and Eye-Tracking Data. Human Factors. *The Journal of the Human Factors and Ergonomics Society, 49*(3), 347.

Schaefer, A., Collette, F., Philippot, P., Linden, M. V., Laureys, S., Delfiore, G., et al. (2003). Neural correlates of ''hot'' and ''cold'' emotional processing: a multilevel approach to the functional anatomy of emotion. *NeuroImage, 18*(4), 938–949.

Schoofs, D., Wolf, O., & Smeets, T. (2009). Cold pressor stress impairs performance on working memory tasks requiring executive functions in healthy young men. *Behavioral Neuroscience, 123*(5), 1066–1075.

Simpson, J., Snyder, A., Gusnard, D., & Raichle, M. (2001). Emotion-induced changes in human medial prefrontal cortex: I. During cognitive task performance. *Proceedings of the National Academy of Sciences, 98*(2), 683.

Sosnowski, T., Krzywosz-Rynkiewicz, B., & Roguska, J. (2004). Program running versus problem solving: Mental task effect on tonic heart rate. *Psychophysiology, 41*(3), 467–475.

Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. (1996). Heart rate variability: standards of measurement, physiological interpretation, and clinical use. *Circulation, 93*(5), 1043.

Taylor, S., Welsh, R., Wager, T., Luan Phan, K., Fitzgerald, K., & Gehring, W. (2004). A functional neuroimaging study of motivation and executive function. *Neuroimage, 21*(3), 1045–1054.

Thayer, J., Sollers, J., I. I. I., Labiner, D., Weinand, M., Herring, A., Lane, R., et al. (2009). Age-related differences in prefrontal control of heart rate in humans: a pharmacological blockade study. *The International Journal of Psychophysiology, 72*(1), 81–88.

Veltman, J. A. (2002). A comparative study of psychophysiological reactions during simulator and real flight. *The International Journal of Aviation Psychology, 12*(1), 33–48.

Vila, J., Guerra, P., Muñoz, M., Vico, C., Viedma-del Jesús, M., Delgado, L., et al. (2007). Cardiac defense: From attention to action. *International Journal of Psychophysiology, 66*(3), 169–182.

Weltman, G., & Egstrom, G. (1966). Perceptual narrowing in novice divers. Human Factors. *The Journal of the Human Factors and Ergonomics Society, 8*(6), 499–506.

Wilson, G., & Eggemeier, F. (1991). Psychophysiological assessment of workload in multi-task environments. *Multiple-task performance*, 329–360.

Yao, Y. J., Chang, Y. M., Xie, X. P., Cao, X. S., Sun, X. Q., & Wu, Y. H. (2008). Heart rate and respiration responses to real traffic pattern flight. *Applied Psychophysiology and Biofeedback, 33*(4), 203–209.

Ziegler, G., Dahnke, R., Yeragani, V. K., & Bär, K. J. (2009). The relation of ventromedial prefrontal cortex activity and heart rate fluctuations at rest. *European Journal of Neuroscience, 30*(11), 2205–2210.